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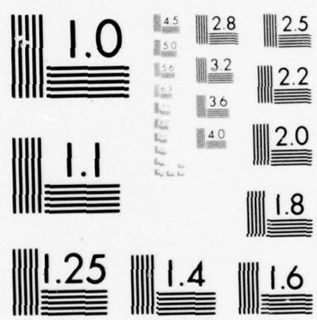

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Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary

J. R. Nelson

A Project AIR FORCE report
prepared for the
United States Air Force

Rand
SANTA MONICA, CA. 90406

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Presents a methodology for life-cycle analysis of aircraft turbine engines that weapon-system planners can use to estimate certain performance/schedule/cost tradeoffs early in the design and selection phase of acquiring this important subsystem. Prompted by the steadily escalating costs of engine acquisition and ownership, the study finds that engine life-cycle costs are much larger than and different from what had previously been realized. For example, depot costs alone will exceed procurement costs for a new engine with an operational lifespan of 15 years. Ownership-data availability being the most serious obstacle, the study recommends that the Air Force begin collecting and preserving disaggregated, homogeneous, longitudinal data at both depots and bases, associated with specific engine types. The findings also suggest numerous improvements in operational and maintenance procedures that the Air Force could adopt in the near term (the Air Force has already initiated studies in some of these areas). Refs. (WH)

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Life-Cycle Analysis of Aircraft Turbine Engines: Executive Summary

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PREFACE

This report is an executive summary of Rand report R-2103-AF, *Life-Cycle Analysis of Aircraft Turbine Engines* (forthcoming). Application of the methodology developed in the study should aid decisionmakers by yielding useful insights into the life-cycle process not only for engines but other aerospace equipment as well. The study was undertaken as part of the project "Methods and Applications of Life-Cycle Analysis for Air Force Systems," sponsored by Project AIR FORCE (formerly Project RAND) and conducted initially within the R&D and Acquisition Program and later within the Logistics Program at Rand. The work was performed during 1975 and early 1976 using data as of 1974. A progress report was widely briefed during 1976 and early 1977.

Utilizing and expanding on earlier Rand efforts in weapon system life-cycle analysis[*] and aircraft turbine engine state-of-the-art assessment and acquisition cost estimation,[†] the present study examines the life-cycle process for this important subsystem in the hope that findings previously obtained at the weapon system level can be corroborated and policy issues clarified.

The report discusses the acquisition and ownership phases of the military engine life-cycle process, the data available for analysis, and model development and application results for each phase. Commercial life-cycle practice is reviewed for lessons that might be applicable to the military situation. The report should be of interest to offices at Hq USAF, the Air Force Systems Command, and the Air Force Logistics Command, where quality and cost tradeoffs during a weapon system's life cycle and the effects of such tradeoffs on meeting a military mission in an era of increasing budget constraints are matters of close concern.

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[*] J. R. Nelson et al., *A Weapon-System Life-Cycle Overview: The A-7D Experience*, The Rand Corporation, R-1452-PR, October 1974; and M. R. Fiorello, *Estimating Life-Cycle Costs: A Case Study of the A-7D*, The Rand Corporation, R-1518-PR, February 1975.

[†] J. R. Nelson and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974.

SUMMARY

This report presents a methodology for life-cycle analysis of aircraft turbine engines, derived from the study of historical data; the data in some instances span 25 to 30 years, and in others only 1 or 2 years. The report also presents numerous findings--some of them surprising--that emerged from study of the data. The findings suggest ways to augment and improve the methodology in the future, and some of them should be of immediate utility to the Air Force for improving engine life-cycle cost estimates and maintenance and operational practices. The study's governing objective is to enable the weapon-system planner to acquire early *visibility* of cost magnitudes, proportions, and trends associated with an engine's life cycle.

The study was prompted by the fact that the costs of acquiring and owning turbine engines have escalated steadily over the years for both military and commercial users. Most of the causes are readily apparent. Demands for higher overall quality--meaning performance, primarily, for the military--have resulted in larger engines that produce greater thrust, run hotter, are costlier to maintain, and entail higher basic engine prices. Material costs associated with engine price have also risen rapidly in the recent past; ov the long term, however, labor costs have risen proportionately more so.

The Air Force has long been aware of these facts, generally speaking; however, one of the major findings of this study is that engine ownership costs are much greater than, and different from, what anyone has previously realized. For example, it now appears that depot costs alone could exceed procurement costs for a new engine with a 15-year lifespan. (In this study, all costs are expressed in constant dollars. Discounting may change some findings, depending on the distribution of cost outlays over the time horizon of interest and the discount rate assumed.)

The chief problem confronting this study, as it has confronted past researchers, is the lack of disaggregated, homogeneous, longitudinal ownership data that are specific to particular engine types,

notably at the Air Force base and depot level. The collection of such data will be necessary for perfecting the methodology, which weapon-system planners can then use to calculate the costs and benefits of a proposed engine for a new aircraft in the early stages of planning and selection; in later phases of the life cycle, logistics managers can use the methodology and the feedback it produces for more effective system management.

The procedure followed in this study was to: (1) develop a theoretical framework for each phase of the life cycle; (2) collect and analyze data for each phase; (3) develop parametric cost-estimating relationships (CERs) for each phase; (4) use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends, and to identify cost-drivers and their effects; and (5) examine commercial experience for cost data and operational and maintenance practices that could be profitable for the Air Force.

The CERs obtained include engine characteristics and schedule variables known to be important to each phase of the life cycle. They also include measures of the quality (benefit sought) and the state-of-the-art advance represented by a particular engine. In its fullest sense, quality embodies not only the performance measures emphasized by the military, but also durability, reliability, maintainability, safety, and concern for environmental effects, all of which are important to the commercial world. The overall balance among quality, schedule, and costs for an engine thus reflects the early planner's estimate of the utility of the product ultimately delivered to the user.

For a new engine that will have an operational lifespan of 15 years, the findings indicate that:

o As mentioned above, engine ownership costs are significantly larger than and different from those found in previously published studies. For instance, engine depot and base maintenance costs, not including fuel and attrition, can exceed engine acquisition costs.

o Depot costs alone can exceed procurement costs.

o Component improvement programs (CIPs) conducted during the operational life of an engine can cost as much as it did to develop the engine to its initial model qualification. A difficulty encountered

in this area has been the aggregated nature of the CIP funds. Prior to 1969, CIP funding did not separate performance growth and additional engine applications from correction of deficiencies and reliability enhancement. Consequently, this study has not been able to ascertain specifically the cost of some magnitude of reliability improvement during an engine's maturation. (The models can be used, however, to estimate the ownership cost reduction realized by improving the actual and maximum times between overhaul.)

o If component improvement and whole spare engine procurement are considered ownership costs, then ownership currently constitutes at least two-thirds of total engine life-cycle cost.

o Satisfying results, both statistically and intuitively, were obtained from modeling performance/schedule/cost relationships for the development and production of military engines; the positive and negative signs for the variables occurred as one would intuitively expect. Mixed but promising results were obtained in modeling ownership costs for military engines. Depot maintenance costs were more detailed and amenable to analysis than base maintenance costs. Because both the depot and base models were derived with sparse data, however, they must be used cautiously until better data and thus improved models become available.

o Application of the models obtained in this study indicates that there is a continuing trend in the direction of higher ownership costs, measured in both absolute dollars and as a percentage of total life-cycle costs. Increasing depot cost is the reason for this trend. To break it, the Air Force will have to depart significantly from its current ownership practices at both depots and bases. The study identifies operational and support policies and procedures that should be strongly supported in attempting to break the trend. Recent efforts with the F100 engine concerning modular design, on-condition maintenance, engine diagnostics, and power management are directed toward counteracting the trend and merit vigorous support. But other policies and procedures beyond the scope of this study are also important.

o Acquisition and ownership costs for engines currently in the Air Force inventory can vary by an order of magnitude between engine

programs and applications; these costs are affected by the engine quality desired, the mission, the schedule imposed on new-engine acquisition, and the operating and support policies selected.

o The engine maturation process must be more fully understood if improved analytical results are to be obtained and applied to new-engine selection. It takes an engine a long time to mature (commercial experience indicates 5 to 7 years). Consequently, average ownership costs are significantly higher during that period than mature-engine, steady-state costs, in terms of dollars per flying hour, the yardstick most commonly used.

To take full advantage of the methodology described here, the study recommends that the Air Force:

o Begin collecting and *preserving* disaggregated, homogeneous, longitudinal data at both depots and bases, associated with specific engine types. Currently, efforts have just begun to separate base maintenance costs by weapon system; and studies of total depot costs for engines do not consistently include, along with overhaul of whole engines, the cost of parts repair during overhaul, the cost of expendable parts, the full cost of replacing condemned reparables, and the repair of components received directly from the field and returned to the field.

o Use the methodology in its current form to estimate the costs of future engines (that is, of any engines that are acquired in the same manner as in the past), and to measure how costs might change if acquisition and ownership were conducted differently.

o Supplement the engine flying hour as the principal measure of the costs of ownership with other outputs such as sorties, takeoffs and landings, engine throttle excursions, and calendar time. With the advent of higher fuel costs, the Air Force may elect to compress flying training into fewer flying hours; if it does so, the total cost of flying may not show a decrease because the cost of a sortie may remain the same or increase.

The Air Force may also wish to consider the following actions, for some of which the rationale derives from commercial experience:

o Expand the awareness of what is entailed for the modular approach to engine design, which is already common in many commercial engines and is beginning to appear in some military engines. Modular design apparently expedites and lowers the cost of maintenance, but requires certain actions which, if not accomplished, negate the expected benefits.

o Monitor full-throttle excursions; even a nominal reduction in hot-time may significantly improve parts life. The F100 engine on the F-15 has an excursion counter, but it is not yet working very well; the new Engine Diagnostic System for the F100 could be extremely beneficial.

o Support efforts to move more in the direction of commercial-style on-condition maintenance, in an attempt to extend the intervals for average time between overhaul (ATBO) and determine the appropriate work to be done.

o Carefully define "quality" and costs in the early phases of weapon system planning. Performance may well continue to be the dominant aspect of quality for the military; but planners should be able to answer such questions as, for example, whether the aircraft's mission makes it worth it to strive for an extra increment of engine performance if the penalty may be higher downtime and additional spare engine and parts procurement, and thus higher overall acquisition and ownership costs. While the technique presented in the study is applicable at the engine subsystem level, final design decisions must be related to the engine's impact on the system, wherein other considerations such as attrition, fuel consumption, and aircraft and installation design characteristics must be weighed and given proper recognition.

When improved and backed up with the proper data, the methodology presented here should supply valuable information with which the initial tradeoffs for the engine can be evaluated.

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CONTENTS

FIGURES

TABLES

SYMBOLS

ATBO = Average time between overhaul, hours

CIP = Component improvement program cost, millions of 1975 dollars

CPUSP = Current production unit selling price, thousands of 1975 dollars

DMQTC = Development cost to MQT, millions of 1975 dollars

DEVTIME = Development time from start to MQT, calendar quarters

EFH = Engine flying hour

EFHC = Engine flying hour consumed by operating fleet

EFHR = Engine flying hour restored to fleet by depot maintenance

KPUSP = 1000th unit production cost, millions of 1975 dollars

LCC = Life-cycle cost

MACH = Maximum flight envelope Mach number (measure of speed related to speed of sound)

MCDUM = Military-commercial dummy (1 = commercial, 0 = military)

MFRDUM = Manufacturer dummy (1 = Pratt & Whitney, 0 = others)

MQT = Model Qualification Test

MQTQTR = Man-rated 150-hr Model Qualification Test date, calendar quarters from 1942

MTBO = Maximum time between overhaul, hours

OPSPAN = Time since operational use began, quarters

PRQTYC = Production quantity cumulative cost at quantity purchased, millions of 1975 dollars

QMAX = Maximum dynamic pressure in flight envelope, lb/ft^2

QTY = Quantity of production engines procured

RDT&E = Research, development, test, and evaluation

RMS = Resource Management System

SFCMIL = Specific fuel consumption at military thrust, sea-level static (SLS), lb/hr/lb thrust

TEMP = Maximum turbine inlet temperature °R

THRMAX = Maximum thrust (with afterburner if afterburner configuration), SLS, lb

TOA = Time of arrival

TOA26 = Time of arrival of demonstrated performance obtained from model derived using 26 military turbojet and turbofan engines, calendar quarters

TOA37 = Time of arrival of demonstrated performance obtained from model derived using 26 military and 11 commercial turbojet and turbofan engines, calendar quarters

ΔTOA26U = TOA26-MQTQTR, calendar quarters

TDC = Total development cost including MQT and product improvement, millions of 1975 dollars

TOTPRS = Pressure term (product of QMAX x pressure ratio), lb/ft^2

WGT = Weight of engine at configuration of interest, lb

I. INTRODUCTION

For we know in part, and we prophesy in part.--I Cor. 13:9

Over the past decade, the Department of Defense has placed increasing emphasis on understanding and assessing acquisition strategies and cost considerations in the development and procurement of new weapon systems. In the present era of budget constraints, and with an increasing share of the DoD budget devoted to operating and supporting forces in being, it has become even more important to be able to measure the contribution of both new and existing weapon systems to the overall defense posture--that is, their benefits relative to their costs.

Consequently, attention has recently focused on attempts to understand and predict total life-cycle costs for new weapon systems and important subsystems, including aircraft turbine engines. They include not only the costs of acquisition (development and procurement) of a new weapon system, but also all the costs of operating and supporting the system in the field during its inventory lifetime. The latter costs for both existing and proposed weapon systems must be more clearly understood to make effective tradeoffs during new developments and procurements. These costs are now a fruitful area for investigation. The main difficulty confronting this study, as it has confronted previous researchers, is the unavailability of disaggregated, homogeneous, longitudinal data associated with specific engine types, particularly at the Air Force base and depot level. The data that are available are largely aggregated and cross-sectional, covering short periods of time; and commercial contractors are understandably reluctant to offer free access to certain proprietary cost information.

OBJECTIVE OF THE STUDY

This study of the life-cycle analysis of aircraft turbine engines has a two-fold objective: (1) to develop a methodology for assessing life-cycle benefits and costs; and (2) apply that methodology to improve understanding of policy options for engine acquisition and ownership.

The problem addressed is the weapon-system planner's lack of detailed information and a methodology to enable him to make early decisions concerning the selection of a new engine within a life-cycle context. Accordingly, this report presents a methodology for life-cycle analysis, derived from the study of historical data on military and commercial engines. This methodology, when backed up with appropriate data collection, should equip the weapon-system planner with improved early *visibility* of the magnitudes, proportions, and trends of costs associated with the various phases of an engine's life-cycle. He should then be able to identify influential parameters that drive costs and exert leverages between life-cycle phases, and thus be able to assess tradeoffs among quality, schedule, and cost in the search for policies appropriate to the various phases of a new engine's life cycle. The methodology can then serve as a *control* or feedback mechanism as the new system is developed, procured, and placed in operational service; the planner can use the information it provides to measure results obtained and use those results in estimating benefits and costs for the next system.

The procedure followed in this study was to: (1) develop a theoretical framework for each phase of the life cycle, one feature of which was use of a technique for assessing the state-of-the-art advance represented by a new engine; (2) collect and analyze data for each phase; (3) develop parametric cost-estimating relationships (CERs) for each phase; (4) use the CERs in examples to ascertain behavior and obtain insights into cost magnitudes, proportions, and trends* and to identify cost-drivers and their effects; and (5) examine commercial practice for cost data and operational and maintenance practices that might be profitable for the Air Force.

BACKGROUND

Aircraft turbine engines are a particularly promising subject for study because: (1) they are extremely important in weapon-system

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*Use of this procedure implies that the future will behave like the past; consequently, the results here apply to a "will-cost" context rather than a "should-cost" context. "Should cost" implies changing the structure and behavior of the current institutional arrangement.

applications; (2) they are felt to be the pacing subsystem in aircraft weapon-system development; (3) they represent a large inventory and budgetary expense; (4) their 30-year history of continuing technological improvement furnishes a sizable (though fragmentary) data base for analysis; and (5) they could provide insights, from a subsystem viewpoint across the life-cycle spectrum, that may be readily applicable to the weapon-system level. The subject also has an immediate practical urgency: engines are a topic of considerable interest today because of problems arising in the operational inventory with aircraft grounded owing to engine-related problems.

Previous Rand studies have dealt with aircraft turbine engines, and some of Rand's engine cost-estimating work goes back over a decade. More recently, this research has turned to the problem of measuring the stace of the art in turbine engines and relating this measure to development and procurement costs in an attempt to evaluate tradeoffs in performance, schedule, and cost.(1) That methodology will be investigated in this study for possible extension to ownership cost, to assist in providing an overall methodology for estimating total life-cycle cost.

RESULTS OF PREVIOUS STUDIES

Many past studies have attempted to shed light on the engine life-cycle process, and current studies within the Air Force and the DoD community are extensively involved in life-cycle cost estimates. The central question is, How much does it cost to acquire and own a military engine over its life cycle? No previous study has been able to answer that question fully.

The most recent studies examined have been more qualitative than quantitative, or have addressed only a portion of the life cycle.* Previous studies have attempted to quantify operating and support costs and total life-cycle costs for specific engines, but no study to date

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*Studies by ARINC, LMI, JLC Panel, NASA, GAO, SAB, and most recently, PMR/HQUSAF, where some data were presented, but no cost-estimating methodology. The PMR study provides brief summaries of most of the other major studies. (See Refs. 2-8.)

has clearly defined *all* of the relevant cost elements and obtained their associated actual costs for any ongoing engine program. The lack of data is the persistent obstacle in the path. For existing engines in the USAF inventory, studies of operating and support costs have been performed with cross-sectional data; in most cases, they cover only a single fiscal year or even less. For a new engine, the procedure has been to select a closely similar existing engine and use modified cross-sectional data from that engine's current experience in an attempt to project operating costs over the proposed engine's entire life cycle. The combined lack of longitudinal data and of a reliable methodology for projecting detailed cost estimates over a new engine's life cycle have frustrated such attempts. Furthermore, none of these previous studies have attempted quantitative calculations of the effect of state-of-the-art advances on life-cycle costs.

All these difficulties have led earlier studies into the erroneous conclusion that engine base and depot maintenance costs are a relatively minor fraction of total life-cycle costs for an engine--as little as one-tenth to one-fifth, with the range being affected by whether or not fuel consumption attributed to a mission was considered within the total cost estimate. The rest of the cost, then, was perforce attributed to the acquisition phase.

These earlier studies suffered from the difficulty of defining the cost elements associated with each of the phases of the life cycle, and ascertaining whether these cost elements were consistent over time and whether all relevant cost elements were indeed included; their results further depended heavily on the data sources and assumptions they employed. For instance, hourly labor rates used to estimate base and depot labor costs will vary markedly, depending on the extent to which the direct labor cost is burdened by applying appropriate overhead charges. Many studies have omitted significant portions of the direct labor-hour cost burden. Another difficulty lies in assuming that cross-sectional operating and support costs are average costs sustained over the entire life cycle. The cross-section is likely to have been taken either during the steady state of a mature engine or during its immature dynamic state; since neither state is "average," a cross-section can seriously distort the estimate either up or down.

Previous studies have estimated engine ownership costs in a range of \$20 to \$200 per engine flying hour. Recent data obtained for this study indicate that costs can be several times higher (even after adjusting for inflation) for the newer, high-technology engines. It is possible that some previous cost figures were valid for earlier weapon systems, but current systems are tending toward considerably higher operating and support costs, and future systems threaten to be even more costly if no actions are taken to change the direction of this trend.

OUTLINE OF THE STUDY

This study examines the magnitudes, proportions, and trends of costs for acquiring and owning a new aircraft turbine engine and highlights the parameters driving these costs for the benefits sought. It provides an overall life-cycle methodology that incorporates the effect of state-of-the-art advances required for new engines.

Section II discusses the objectives, definitions, and data requirements for life-cycle analysis. Section III presents the results of life-cycle analysis for military engines. Section IV discusses applicable commercial experience. Conclusions and recommendations are presented in Sec. V.

II. LIFE-CYCLE ANALYSIS

The life-cycle analysis of a new weapon system must be based on an understanding of all phases of the life-cycle process, both separately and as they interact. They include concept formulation, validation, development, procurement, deployment, operational use, and disposal. The life-cycle process extends over two to three decades, depending upon the quality originally sought and the quality obtained, the length of time spent in each phase, and the importance of the system in the inventory. The creation of a weapon system involves many organizations within the Government, military services, and private industry. While life-cycle analysis must be sensitive to institutional practices, the central concern of this study is to develop a methodology that can be applied to benefit/cost tradeoffs.

DEFINITIONS AND QUANTITATIVE MEASUREMENT OF BENEFITS AND COSTS

It is often extremely difficult to evaluate quantitatively the benefits to be gained from a new weapon system. For example, the new system may incorporate a technical characteristic that appears to provide a marginal improvement at best over a previous system, but in reality creates a significant combat advantage--but how is that advantage to be measured? In the commercial arena, the bottom line is profit earned for the service provided (where safety is one implied part of service), but it is far from easy to assign a dollar-equivalent to the benefits a weapon system produces in a wartime environment. In attempting benefit and cost assessments for engines, it must also be recognized that analysis at the subsystem level must ultimately be related back to the system; engine output must be measured in terms of its contribution to the weapon system. The true measures are the engine's impact on weapon-system availability and utilization, mission reliability, effectiveness, mobility, and inventory life. Such measures are beyond the scope of this study, which confines its measure of output to the subsystem level. It is the task of the weapon-systems planner to transform the output measures dealt with in this study into the ultimate

value of the system; the methodology presented here should enable him to do so with more confidence than has heretofore been possible.

DEFINING BENEFIT MEASURES FOR AIRCRAFT TURBINE ENGINES

The aircraft turbine engine has been characterized as one of the highly significant inventions of the twentieth century. Certainly, no one can deny the tremendous importance of the changes its military and commercial applications have wrought on our history and the way we live. But in this era everything comes with a price-tag. It has been said, somewhat wrily, that the only trouble with a turbine engine is that it weighs something, it gulps fuel, it takes up space, it creates drag, and it breaks now and then. Like all other inventions, it has its benefits, and it has its costs.

Benefit measures for an engine hinge on its design, how it is used, and how it affects weapon-system quality.

Quality is an extremely complex measure that defies absolute quantification in a military context. For an engine, it embraces the sum of the characteristics it is to contribute to a new weapon system (performance, durability, reliability, maintainability, safety), just as life-cycle cost is the sum of all cost elements. However, military quality is partly a subjective matter, more difficult to assess than cost. How much is an extra 50 miles per hour worth to a fighter aircraft? What is it worth to have the aircraft available more frequently? In the weapon system context, it is possible--and necessary--to arrive at rational dollar figures for the answers, but subjective judgment will always enter the calculations.

In a life-cycle analysis, we seek to clarify, at least in part, the tradeoffs among product quality, schedule, and total cost. When one characteristic of an engine is changed, other characteristics are affected. *Since quality is a combination of many things, it is not certain that an improvement in one characteristic of quality necessarily leads to an overall improvement in quality for the end use desired.* For instance, if performance is increased to the detriment of reliability, it is not clear that overall quality is improved. In this study, quality is considered closely synonymous with performance in a military

context, and engine performance characteristics are related to the state of the art to assess their schedule and cost impacts in selecting a new engine.

For military systems, quality has primarily meant performance, with other characteristics considered secondary. The goal commonly has been to obtain thrust at a minimum fuel consumption, weight, and installed volume, but other characteristics should be considered. (Commercial practice emphasizes safety, reliability, and cost.) Durability and reliability are so closely related that they are somewhat difficult to distinguish; but durability can be related to design life, the engine's continuing ability to perform the mission in the aircraft during its inventory lifetime. This may entail consideration of several system output measures: flying hours, sorties, takeoffs and landings, engine cycles (throttle movement), and calendar time. Reliability can be expressed as the engine's ability to be ready to go on any given mission and to perform it successfully. Measures of interest are engine removal rates, mission aborts, and time between scheduled base maintenance and depot repair visits. Maintainability is the ease with which the aircraft/engine combination can be maintained in the field. Safety can include design features that may appear to detract from performance--for example, designing engine casings so blades cannot go through them if they separate from the rotor. Such a feature increases engine weight but reduces the chance of substantial airframe damage. Environment impacts include noise and smoke, which can be reduced at some penalty to engine performance.

The most widely used output measure of ownership cost for a given engine is *cost per engine flying hour*. In the future, however, other measures may become more relevant. With the advent of the high cost of fuel, flying training may be accomplished in fewer flying hours. But pilots can make fuller use of these flying hours so as not to cut down on critical portions of their training. Thus, in the future, flying hours may decrease, but not the number of sorties, takeoffs and landings, and engine cycles; if so, cost per flying hour may not be an appropriate measure. The cost of maintaining the engine inventory may not decrease even though there is a decrease in flying hours and fuel

cost. This is especially true if maintenance is staffed to handle peak workloads in wartime. Another measure is calendar time. The longer an engine is out in the field without major depot rework, the more opportunity it has to undergo corrosive and secondary damage. When it does finally return to the depot, the damage may be more extensive than might be expected on the basis of flying hours alone.

Although this study will primarily use *engine performance* characteristics to relate to state-of-the-art and life-cycle costs, and the *engine flying hour* as an output measure for ownership costs, future data collection efforts should encompass other benefit measures--notably, sorties, takeoffs and landings, engine throttle excursions, and calendar time.

DEFINING LIFE-CYCLE COST ELEMENTS*

The life-cycle cost of an aircraft turbine engine is the sum of all elements of acquisition and ownership costs. To enable effective tradeoff decisions, detailed definitions of those elements are necessary, particularly in terms of what belongs under acquisition cost and what belongs under ownership cost. Table 1 lists those elements as they are used in this study. There are three columns in the table: (1) engine acquisition costs, comprising the RDT&E and procurement portions of the acquisition phase involving design, development, test, manufacture, and delivery to the field; (2) engine ownership costs, comprising operating and support maintenance costs for all base and depot activities; and (3) weapon-system-related costs for fuel and for attrition due to accidents and catastrophic failures.

Certain cost elements appear under both "acquisition" and "ownership" as, for instance, ECP/mod/retrofit costs. In one situation, they can be in the "acquisition" column because they are associated with enhancement of performance or a change in requirement that should be attributed to acquisition. In another situation, they can be associated with changes for correction of a deficiency and improvement of

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*In this study, all costs are expressed in constant dollars. Discounting may change some of the findings presented in Sec. III, depending on the distribution of cost outlays over the time horizon of interest and the discount rate assumed.

Table 1

CLASSIFICATION OF LIFE-CYCLE COSTS

Cost Element	Acquisition	Ownership	Weapon-System-Related
RDT&E	X		
Flight test	X		
Tooling	X		
Proc. of install engine	X		
CIP		X	
Spare engine		X	
Spare parts (base/depot)		X	
Depot labor		X	
Base labor		X	
ECPs--mod/retro	X	X	
AGE (peculiar/common)	X	X	
Transportation	X	X	
Management	X	X	
Facilities	X	X	
Training	X	X	
Engine attrition			X
Fuel			X

reliability and thus are attributable to ownership. Other costs appearing in both columns include AGE (common and peculiar), transportation, management, and training. These cost elements are not usually large in either acquisition or ownership (on-the-job training is significant, but difficult to separate from all other maintenance labor costs at the base or depot; also, initial recruitment training is not considered here). Facilities are usually a one-time expenditure and vary widely from program to program. They are included in the definition, but will not be considered further in this study. With the increasing complexity of new weapon systems, peculiar support equipment may become increasingly costly, particularly if it is considered to include software design and development as well as hardware, and if simulators and diagnostic systems are regarded as support equipment. This should be considered in future systems, particularly if engine health monitoring becomes an increasingly important factor in the design of new engines.

Engine attrition and fuel are classified as weapon-system-related because these cost elements depend primarily on the design and use of

the particular weapon system. (Fuel consumption is a function not only of engine design but also of mission use; attrition rates depend on single-engine versus multi-engine application as well as other features.)

AIRCRAFT TURBINE ENGINE DATA

Researchers attempting a life-cycle study of a weapon system constantly run up against the same obstacle: obtaining all the relevant data required. The problem is much like trying to put together a jigsaw puzzle when some of the pieces are missing and other pieces seem to have wandered in from another similar puzzle. Not only must the researcher comb through a large number of data systems, but there is the additional problem of inconsistency of data sources--two different data systems not agreeing when both supposedly use the same data from the same basic source.

The data most readily available for ownership cost-estimating in this study have been aggregated, heterogeneous, and cross-sectional, that is, gross, weapon-system-level or engine-family cost totals for only a few fiscal years and sometimes inconsistently defined across those years. A sound life-cycle analysis requires disaggregated, homogeneous, longitudinal data, cost data broken down below weapon-system level, into consistently defined categories, and available over a considerable period of time, preferably at least ten years. In general, Air Force practice is to save costs for about three to four years.*

For engines, the contractor is the best source of RDT&E/CIP and procurement data, since he is in the best position to break out the detailed cost elements for each portion of the costs associated with a particular contract, and he saves cost data for many years. These data are valuable to him for analyzing new engine programs, whereas the military services, because specific contracts may cover a multitude of

*This is perhaps going to be changed in the near future with several data systems forthcoming at OSD and Hq USAF that may save costs over a longer period of time. VAMOSC (Visibility and Management of Operating and Support Costs, OSD/I&L) and OSCR (Operating and Support Cost Reporting, AFAC) are now being implemented. These systems could eventually also provide the kind of data needed at the subsystem/component level.

III. MILITARY AIRCRAFT TURBINE ENGINE LIFE-CYCLE ANALYSIS

This study extends previous work on acquisition cost-estimation which employed a Time of Arrival (TOA) technique that attempted to include the effect of state-of-the-art changes on costs.[1,9,12] This section briefly summarizes the technique, discusses analysis of the cost data collected during the study, and presents the models obtained and an example of the application of these models.

THE CRITICAL NATURE OF THE ASSESSMENT OF AVAILABLE TECHNOLOGY

A critical problem is to assess the available technology base for the product desired. The current technology base is not always able to produce the quality desired, and some finite amount of technological advance is therefore called for during the development process. The product is then pushing the state of the art, and the required advance will entail additional cost; if the advance is not achieved, the penalty will be lesser quality, higher cost, and the loss of time or resources or both expended on the unsuccessful effort. These events can occur when the technology base and the desired advance are not assessed properly during the early design phase. *If the technology is in hand, it may be costly not to use it to obtain the product desired. If the technology is not in hand, it may turn out to be extremely costly to obtain it during full-scale development and procurement of the product.*

METHODOLOGY

As a proxy for technological state-of-the-art advance, this study uses the time of arrival (TOA) of a particular set of aircraft turbine engine characteristics at the 150-hour Model Qualification Test (MQT) date. The variables used in a multiple regression technique to obtain the equation that predicts the TOA are thrust, weight, turbine inlet temperature, specific fuel consumption, and a pressure term that is the product of the pressure ratio and the maximum dynamic pressure of the engine's operating envelope (QMAX). These performance measures are important to successful military engine applications. The initial

items procured by a lump-sum cost, are hard pressed to attempt a detailed breakout of costs long after the fact. For instance, a given Air Force contract may include not only the procurement of whole engines, but some allotment to spare parts, management data, field support, and so forth.

The only source of all relevant ownership data is the using military service. It is critically important to obtain all relevant costs in a particular area. For instance, depot costs are a large expense for engines. The total depot cost includes not only overhaul of whole engines, but also repair of reparable parts for whole-engine overhaul, the cost of expendable parts, modifications, and the repair of components received directly from the field and returned to the field. Some of these costs have not been included in previous studies attempting to obtain total depot costs.

The operating base has similar data problems. This is one area in which specific weapon system costs are significantly lacking. To obtain cost elements at the base, for example, the Resource Management System (RMS) is useful for costs associated with specific base cost centers. This system will provide the cost associated with operating the engine shop. Several difficulties hamper the collection of engine-related base costs: the engine shop is not the only source of labor related to engines; costs associated with the engine shop involve fixing all of the engines on a base, not merely the engine type of interest; and costs are not separated by weapon system. The analyst therefore must exercise care in obtaining the correct costs properly allocated, or apply some estimation technique that includes allocation.

efforts in obtaining a trend for military engines concentrated on performance since these measures were most readily available, and it was felt that the military process was essentially performance-oriented. Many additional variables that were examined did not add significantly to the quality of the model once the above variables were used.

The data base for the model consisted of 26 turbojet and turbofan engines spanning a 30-year period of aircraft turbine engine history. Significant individual advances have occurred in particular areas during this period, but steady evolutionary advancement has been the general theme. Therefore, time is a reasonable proxy for evolutionary state-of-the-art advance when evaluating tradeoffs of performance/schedule/cost considerations in the selection of a new weapon system.

The results of this TOA model appear in Fig. 1, which portrays the model in terms of the number of quarters of years from an arbitrary origin beginning in October 1942, selected because it was the date when the first U.S. turbojet-powered aircraft flew. The equation is displayed in the figure.

The statistical qualities of the model are very good, as shown by the R^2 and standard error (SE). Also, the F and t tests for the model and coefficients were extremely significant. Even more interesting, however, in this and in subsequent work utilizing this technique, is the fact that all the variables in this and other models studied to date have entered into the relationships in an intuitively appropriate manner.

TOA is a function of the technological characteristics of turbine engines. The signs of the coefficients in the TOA equations are consistent with intuitive notions of what constitutes more technologically advanced achievement with time: positive coefficients on variables for which larger values are more difficult to achieve, and negative coefficients on variables for which smaller values are more difficult to achieve. For example, as technology advances, one would expect pressure and turbine temperature to increase, and both do have positive coefficients in the equation. One would expect certain other variables to decrease as technology advances, such as weight and specific fuel consumption, and these do have negative coefficients. Thrust has a

positive coefficient, indicating that, on the average, the physical size of engines has grown over the 30-year history. Engines are considerably larger today in terms of thrust than they were 20 to 30 years ago. In Fig. 1, the Time of Arrival, TOA26, is plotted on the ordinate against the actual time of arrival on the abscissa for the 26 data points as shown. The 45-degree line can then be visualized as a measure of the state of the art. If an engine calculated to arrive on a certain date does indeed arrive on that date, it falls on the 45-degree line. Data points above the 45-degree line would represent advanced engines in the sense that they were calculated to arrive on a certain date but arrive earlier. They are ahead of their time. Conversely, engines below the 45-degree line would be considered conservative. The standard error is shown by the dashed lines.

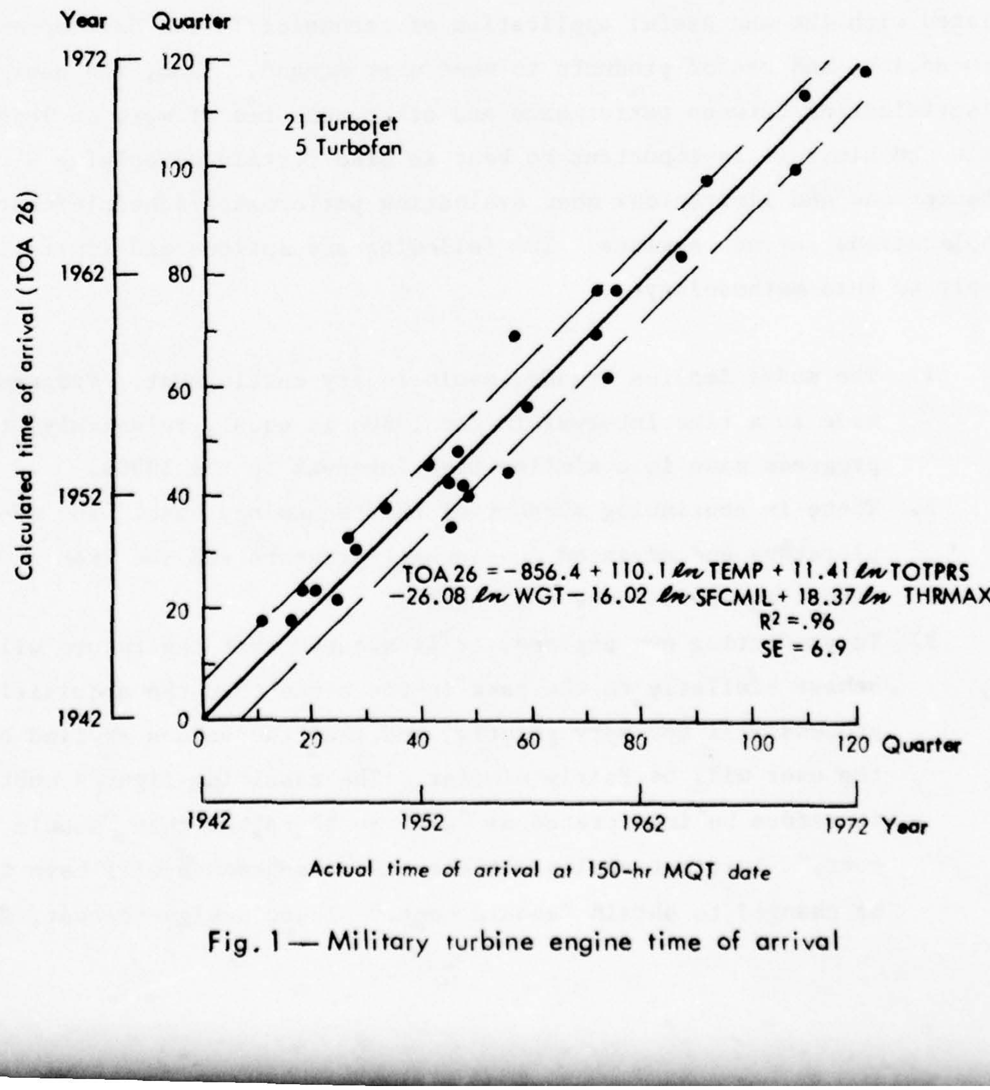

Fig. 1 — Military turbine engine time of arrival

Of particular interest during early planning at the conceptual phase would be an engine falling outside the standard error on the high side, namely, a significantly advanced engine in terms of the data base. The difference between the engine TOA and the 45-degree line is defined as ΔTOA, a measure of the advance required of the engine for the performance characteristics desired relative to the trend.

The methodology does not indicate that such an advanced engine cannot be achieved, but it would indicate that it is more difficult than achieving an average engine. It is reasoned that any attempt to achieve such an advanced engine has a higher exposure to performance shortfall and schedule slip and, as will be shown subsequently, such an engine is more expensive to develop and procure.

It must be emphasized that the time-of-arrival methodology is not a trend of technology, per se, but a time trend of the parameters associated with the successful application of technology: the development, production, and use of products to meet user demand. Thus, the user is discriminating between performance and other measures of more or less value to him. It is important to bear in mind certain underlying assumptions and limitations when evaluating performance/schedule/cost implications for new engines. The following assumptions and limitations apply to this methodology:

1. The model implies steady, evolutionary development. Progress made in a time interval in the 1950s is equal, relatively, to progress made in a similar time interval in the 1970s.
2. There is continuing support of the technology base. The exploratory and advanced development programs and the IR&D effort are continuous and ongoing.
3. In predicting new engines, it is assumed that the future will behave similarly to the past in the sense that the acquisition process will not vary greatly, and that the values applied by the user will be fairly similar. The resulting figures must therefore be interpreted as "will cost" rather than "should cost." Institutional practices and arrangements will have to be changed to obtain "should cost." Thus, design-to-cost, as

opposed to the current military philosophy of design-to-performance, must still be evaluated cautiously in a military context. However, by combining military and commercial experience, new insights may be obtained concerning the value of characteristics other than performance in attempting to obtain an overall trend of quality in an engine.

4. In predicting the future, it is important that the variables associated with new products be a reasonable extension of the data base variables. Near-term future predictions are therefore likely to be more valid than far-term predictions. The variables must certainly be internally consistent with regard to thermodynamic cycle characteristics for the design being evaluated.
5. The data base is for all industry products, and the models reflect average industry experience. Thus, the models may not totally reflect a particular manufacturer, since there are leaders and followers in any industrial and technological area.

DATA ANALYSIS

Data were obtained and analyzed prior to development of CERs. Development costs for 14 military turbojet and turbofan engine programs and procurement costs for 18 such programs were obtained and used to generate acquisition cost models utilizing TOA and ΔTOA. Reference 1 contains a detailed discussion of the data and their treatment. These data were obtained almost exclusively from contractors. Ownership data, on the other hand (except for CIP), were obtained mainly from Air Force organizations. These data were severely limited as to quality and time span, limiting the model results that could be obtained in this area. Interesting insights were obtained concerning magnitudes and proportions of costs for particular ownership expenses, and some model results are useful as crude estimates of costs.

COMPONENT IMPROVEMENT PROGRAM COSTS

CIP data were collected for eight major engine programs. Analysis of the data indicates that more money has been spent on CIP than was

spent to get to the original MQT. The costs for RDT&E do not include engine-related costs associated with weapon-system flight testing, and the CIP costs do include performance enhancement and additional applications within a specific engine program as well as corrections of deficiencies, reliability improvements, and cost reduction, since this is the way cost data were collected prior to 1969. In terms of 1975 dollars, the eight engine programs required \$1.9 billion to achieve MQT. They have required a total of \$5 billion to date for total development, i.e., the combined MQT and CIP costs which, in some cases, have stretched over two decades. As mentioned above, these costs do contain the performance growth and application enhancement funds, which are substantial in any program. It would be useful in future analyses to attempt to separate the performance and application monies from data prior to 1969 (when accounting practices changed), so that a model might be developed on the basis of the current definition of CIP, which allows only for correction of deficiencies, reliability improvement, and cost-reduction activities.

DEPOT COSTS

The primary function of the USAF engine depot is to overhaul engines and accessories to restore them to what is termed a "zero-time" status, allowing the overhauled hardware to be flown again to the maximum time allowed by maintenance policy decisions. Besides this primary function, several other engine-related repair activities go on at a depot. They include immediate correction of hardware deficiencies that are causing safety-of-flight problems and could result in grounding of the fleet; minor repairs of engines that do not need major repairs, but such repairs must be accomplished at a depot rather than a base; modifications to engines to replace parts that have been obsoleted for deficiency or reliability reasons; repair of reparable parts and accessories removed from returned engines or sent in from the field; and replacement of reparable parts and accessories that are condemned.*

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*System Support Stock Funds for expendable parts must also be included, either as a direct cost or as an added charge to the direct labor-hour cost.

For new weapon systems entering the inventory, initial spares stockage costs must also be accumulated. To understand the true cost of operating a depot, all of these activities and their associated cost elements must be identified and accumulated.

The primary measure of benefit used in this study is the engine flying hour. In examining the depot portion of an engine life cycle, there are two views of this benefit for estimating costs at the depot: the engine flying hours consumed by the aircraft fleet during operational activity, and the engine flying hours restored to the fleet by the depot repair activity. Under steady-state conditions, it is expected that fleet demand equals depot supply, so that consumed flying hours (demanded by the user) would approximate restored flying hours (supplied to the user from the depot). However, in any given year this is not necessarily the case. Heavy utilization could result in more consumed than restored hours, or a large modification program could result in more restored than consumed hours. Moreover, a new engine program consumes more flying hours initially than depot activities restore, as flight operations build up; and over the life cycle as a whole, flying hours consumed exceed flying hours restored because obsolete engines are not repaired prior to disposal. Thus, both flying hour measures are of interest.

What does a depot repair program for an engine cost? From the data analyzed, it appears that a single overhaul costs about 10 to 20 percent of the current procurement cost of that engine (in constant dollars). Modifications to engines inspired by serious flight deficiencies not associated with zero-timing the engine will result in additional costs for that engine at the depot and the costs will vary with the maturity of the engine. In addition, MISTR support for components returned from the field, and the replacement of condemned reparable parts and accessories during their repair, can add 10 to 100 percent to the total engine program overhaul cost in any given year.

An engine, on the average, can go through overhaul at the depot three to six times or more during a 15-year operational life cycle. Subsonic transport engines fall at the lower end of the range, and supersonic fighter engines at the upper. Average time between overhaul

(ATBO) is substantially less than maximum time between overhaul (MTBO), particularly in the early maturation period of an engine; consequently, average actual repair times are of primary interest for depot costs. Engines seem to go to overhaul more frequently in their earlier years and cost more to overhaul in later years, because parts in older engines are more often condemned and replaced; thus, the situation must be viewed in a total context, not solely in a mature engine steady-state context.

When the single overhaul cost, added support costs, and frequency of depot visit are combined, the results indicate that *total depot costs for an engine during a 15-year operating span can exceed its procurement cost.*

BASE COSTS

As mentioned earlier, specific weapon-system-related costs are significantly lacking at the base level. Bases apparently do not have a single integrated data source for all costs related to engine maintenance. Accordingly, this study uses data from a variety of sources to estimate the base labor and parts costs for selected engines in the Air Force inventory.

Engine costs at the base are related to maintenance labor, parts, and support for the following activities: unscheduled flight-line maintenance; unscheduled maintenance in the shop, including removal and replacement of engines and accessories; periodic scheduled maintenance (including base-installed modifications); engine test and checkout before reinstallation; and removal and replacement when an engine is to be returned to the depot. Existing maintenance data indicate that from one-half to two maintenance man-hours are expended per flying hour on the engines of a variety of weapon systems. In using such data, however, the analyst must take care that they cover all engine-related work--not only unscheduled maintenance, but also scheduled maintenance and engine-related accessories--and that they exclude repair of aircraft-related engine-mounted accessories (QEC items). Also, such data represent labor utilized. When available engine shop personnel are counted, the maintenance labor available is on the order of one-half

to two maintenance man-years per possessed engine on the base; this can translate into three to six maintenance man-hours per flying hour, depending on the particular weapon system and its flying hour program.

Available manpower is what the Air Force is paying for in terms of total maintenance labor cost. A policy has been determined concerning the necessary manning for a wartime contingency (the number of personnel required to support the weapon system in a wartime environment), and the Air Force is paying for that level of labor, even if it is not fully utilized in peacetime.

At present, one approach to the base cost of maintenance labor for an engine is to examine the Unit Detail Listing. As indicated above, data from several selected bases indicate that maintenance labor will vary from one-half to two maintenance man-years per possessed engine depending on the particular engine. Some administrative and support costs must be added to this direct labor cost (a 50-percent add-on is assumed here). Thus, one maintenance man-year is estimated to cost \$10,000 in direct labor and an additional \$5000 in indirect costs, for a total of \$15,000 per maintenance man-year. Expendable parts must be estimated (a range of from more than \$1000 to less than \$5000 per engine per year is indicated for the first-line engines, again depending on the engine*) from an examination of RMS, depot supply, and engine manager accounts. It appears that although this total base cost may be less than depot costs for most engines, it is a signficant amount.

SPARE ENGINES

Spare engines add approximately 25 to 50 percent to the installed engine inventory in the Air Force, and thus account for at least 20 percent of the total procurement cost of engines for a weapon system. They also have the effect of diluting the number of expected flying hours per engine over the life cycle. Thus, an engine designed and

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*For instance, the J79-GE-17 on the F-4E at Seymour Johnson AFB, North Carolina, requires about 2/3 maintenance man-year per possessed engine for the base, and supply accounts indicate about \$1500 per engine per year in expenditures for FY 1975. On the basis of 200 flying hours per engine per year, a cost of \$57.50 per engine flying hour would be estimated for base support.

purchased with the expectation of operating for 5000 flying hours within a specified life-cycle will probably fly only around 4000 hours during this period, on the average, if the engine has a 25-percent spares ratio. The spares ratio appears to be application-oriented, in that the lower percentages appear to apply primarily to the subsonic transport and bomber aircraft while the higher percentages pertain more to attack and supersonic fighter applications. The cost of spare engines can be handled directly when computing the total cost for quantity of engines procured during a weapon system's lifetime, assuming a spare engine ratio. Spare engines bought during the same period as the installed engines should have the same progress slope applied, and indeed, should help in reducing the cost of future engines. The spares merely add to the quantity of installed engines to be bought. But how many spare engines do you buy?

There is a specific computation for obtaining the number of spare engines a weapon system is expected to require.* On the basis of factors such as programmed flying hours, number of installed engines on the aircraft, number and location of operating bases, and where certain repairs of the engine are to be made, a requirement is established for a specific number of spare engines to fill the pipeline at the base and between the base and the depot. Specific numbers of days are estimated for the time it will take a base to turn an engine around and a depot to process an engine at overhaul. The spare engines serve as replacements for failed engines that are removed for repair. A fill-rate objective is specified in terms of the ability to meet the demand for a spare engine. If the demand cannot be met, it is called a back order, which is defined as an aircraft requiring an engine. Given the fill rate and a certain number of spares at a base, an expected effectiveness rate can be calculated--that is, the rate at which aircraft have their spare engine requirements satisfied and again become operational. A

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*The standard computation procedure is DODI 4230.4, *Standard Method for Computation of Spare Engine Procurement Requirements*. The Systems and Resources Management Advisory Group also studied the spare engine situation and recommended reexamination of spare engine procurement with the idea that the Air Force might be able to reduce spare engine procurement without degrading combat support capability.

confidence level is also associated with this process. For combat aircraft, the confidence level is presently required to be 80 percent. Spare engine requirements are estimated on the basis of the minimum quantity of engines essential to support the programmed peacetime or wartime engine operation, whichever is greater. Since wartime flying is usually programmed at a higher rate, it is to be assumed that the spares are applicable to the wartime posture. Thus, spare engines are intended to reflect wartime requirements in terms of a fill-rate objective and effectiveness rate at some confidence level. Usually, more spare engines are purchased early in a new weapon system program, and then phased down to the computed requirement as experience is gained. But the computed wartime requirement could still be higher than is necessary, particularly if appropriate consideration is given to attrition and duration of the conflict.*

No parametric model was obtained in this study to enable an early planner to predict the appropriate spares ratio for a particular application.

OTHER COSTS

Other operating and support costs besides depot and base maintenance (and fuel and attrition) contribute to the total life-cycle cost of an engine. They include:

1. Transportation
2. Ground support equipment
3. Management
4. Training
5. Facilities

The above costs appear to add not more than 5 percent to all costs previously discussed (not including initial recruitment training or a

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*A study under way at Rand concerning this issue indicates this to be the case.

major facility expenditure). Thus, increasing the total life-cycle cost for an engine by 5 percent should encompass all of the costs identified here for acquisition and ownership.

LIFE-CYCLE COST MODELS

The TOA methodology for relating performance to development schedules has been incorporated into cost-estimating relationships (CERs). TOA and ΔTOA were investigated along with other variables felt to be important. Reasonable CERs were obtained for military engine development and procurement costs, where homogeneous, disaggregated cost data were available from the contractors for a 25-year period. Without this type of data, meaningful relationships could not have been obtained. The approach was to investigate variables considered important in the development and procurement phases of a new engine. The approach was then extended to the ownership phase of the engine life-cycle to obtain more comprehensive models for total engine development, component improvement, and depot and base maintenance costs. The model results are portrayed in Table 2.

Again, in all the cost models studied, the variables have entered the relationships in an intuitively appealing manner. The signs of the coefficients are in the right direction in terms of what an engine designer would expect concerning changes in these variables and the resultant impact that such changes would have on cost. For instance, in the development cost model, development time entered positively, indicating that the longer the program, the higher the cost.[*] The other variables in this model also indicate rational results. Thrust enters positively. The larger the engine, the higher the development cost. ΔTOA and Mach number, related to the state-of-the-art increment to be obtained (or additional time increment required) in the development

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[*]It must be noted, however, that a minimum development time on an order of four to five years for a new engine program must be associated with this estimating relationship, since in the extreme, this relationship could result in zero development cost at zero time. There are physical time constraints with regard to developing a new engine regardless of how simple the engine may be in terms of available technology; thus, there is a minimum development time that must be employed in this model.

Table 2

MILITARY LIFE-CYCLE ANALYSIS MODELS

(1975 Dollars)

State-of-Art Trend:

$R^2 = .96$
SE = 6.9
F = 92.0 (5,20)

$$\mathrm{TOA26} = -856.38 + 110.10\underset{(5.8)}{\ln \mathrm{TEMP}} + 11.41\underset{(3.1)}{\ln \mathrm{TOTPRS}} - 26.08\underset{(5.1)}{\ln \mathrm{WGT}} - 16.20\underset{(2.8)}{\ln \mathrm{SFCMIL}} + 18.37\underset{(2.8)^{a}}{\ln \mathrm{THRMAX}}$$

Development Cost ($M):

$R^2 = .96$
SE = .18
F = 55.7 (4,9)

$$\ln \mathrm{DMQTC} = -1.3098 + 0.08538\underset{(7.6)}{\mathrm{DEVTIME}} + 0.49630\underset{(7.1)}{\ln \mathrm{THRMAX}} + 0.04099\underset{(4.9)}{\Delta \mathrm{TOA26}} + 0.41368\underset{(2.3)}{\ln \mathrm{MACH}}$$

Component Improvement Cost ($M):

$R^2 = .88$
SE = .29
F = 60.5 (3,22)

$$\ln \mathrm{CIP} = -2.79026 + 0.78862\underset{(9.1)}{\ln \mathrm{THRMAX}} + 0.04312\underset{(5.7)}{\Delta \mathrm{TOA26}} + 0.00722\underset{(2.5)}{\mathrm{OPSPAN}}$$

Total Development Cost ($M):

$R^2 = .94$
SE = .18
F = 114.8 (4,29)

$$\ln \mathrm{TDC} = 0.97355 + 1.2\text{[illegible]}809\underset{(10.3)}{\ln \mathrm{MACH}} + 0.07345\underset{(6.8)}{\ln \mathrm{QTY}} + 0.40386\underset{(8.5)}{\ln \mathrm{THRMAX}} + 0.00918\underset{(2.1)}{\Delta \mathrm{TOA26}}$$

1000th Unit Cost ($M):

$R^2 = .95$
SE = .215
F = 63.0 (4,13)

$$\ln \mathrm{KPUSP} = -8.2070 + 0.70532\underset{(9.2)}{\ln \mathrm{THRMAX}} + 0.00674\underset{(2.8)}{\mathrm{TOA26}} + 0.45710\underset{(2.6)}{\ln \mathrm{MACH}} + 0.01804\underset{(2.4)}{\Delta \mathrm{TOA26}}$$

Cumulative Production Quantity Cost ($M):

$R^2 = .97$
SE = .22
F = 501.7 (6,81)

$$\ln \mathrm{PRQTYC} = -7.8504 + 0.8697\underset{(45.)}{\ln \mathrm{QTY}} + 0.82204\underset{(24.)}{\ln \mathrm{THRMAX}} + \underset{(6.)}{\mathrm{MFRDUM}} + 0.01858\underset{(5.)}{\Delta \mathrm{TOA26}} + .34478\underset{(4.)}{\ln \mathrm{MACH}} + 0.00277\underset{(2.4)}{\mathrm{TOA26}}$$

Depot Maintenance Cost Per Engine Flying Hour Restored ($/EFHR):

$R^2 = .97$
SE = .22
F = 67.6 (4,7)

$$\ln \mathrm{DCEFHR} = 2.76182 - 0.90604\underset{(10.2)}{\ln \mathrm{ATBO}} + 1.26074\underset{(4.2)}{\ln \mathrm{CPUSP}} + 0.01104\underset{(2.2)}{\mathrm{OPSPAN}} - 0.02245\underset{(1.9)}{\Delta \mathrm{TOA26}}$$

Base Maintenance Cost Per Engine Flying Hour Consumed ($/EFHC):

$R^2 = .79$
SE = .26
F = 10.0 (3,8)

$$\ln \mathrm{BMCEFHC} = 3.50819 - 0.47457\underset{(4.5)}{\ln \mathrm{MTBO}} + 0.01299\underset{(2.2)}{\mathrm{OPSPAN}} + 0.56739\underset{(1.6)}{\ln \mathrm{CPUSP}}$$

NOTE: See List of Symbols for definitions of terms.

[a] t statistic.

(reflecting the technology reach in the program) and complexity of the engine due to the environment in which the engine has to operate, enter positively. Thus, the development cost model and the 1000th Unit Production Cost model are basically the same as previously reported,[1] except for conversion to 1975 dollars. The total development and component improvement cost models reflect the addition of several data points and thus are slightly different from the models previously reported. Both are included so that alternative methods can be used to compute total development cost. One model depends on quantity of engines procured, while the other depends on the total time in operational service (OPSPAN).

Several variables had to be introduced in developing the production quantity cost model. One was a manufacturer's dummy because of the significantly different accounting practices used by one of the manufacturers before 1971. The most significant variables are quantity and THRMAX. Certainly, quantity should be most significant in this type of model and the thrust level again is a measure of the physical size of the engine to be produced. Again, alternative methods of computation can be employed for obtaining total production cost: either the production quantity model, which contains industry average learning, or the 1000th Unit Cost model and an assumed progress slope that can reflect a manufacturer's learning experience.

A model for total depot cost per engine flying hour restored at the depot (by zero-timing the engine) was obtained as shown in Table 2. The variables found to be significant are the average time between overhaul (ATBO), current production unit selling price (CPUSP), operating span (OPSPAN), and increment of time-of-arrival at the initial MQT (ΔTOA26). Again, they enter with intuitively appealing signs for the dependent variables. For instance, efforts to extend ATBO would reduce depot costs. The cost model using engine hours restored at the depot provided better results than using the cost data related to fleet-consumed flying hours. The difference between restored and consumed flying hours can be substantial in a given program.

An attempt was made to relate base costs to parameters of interest in order to obtain a base cost-estimating relationship. The results are interesting in indicating explanatory variables, but the model should be viewed cautiously because of the nature and limitations of the data. For base maintenance costs, MTBO (the policy-determined maximum time between depot overhaul) was most significant, entering the relationship negatively. Thus, efforts to extend MTBO would reduce base costs, since base periodic scheduled inspections are directly related to MTBO and are a significant portion of propulsion shop activity. OPSPAN entered positively; the longer an engine is in operational service, the more costly it is to maintain at the base. CPUSP entered positively; the more expensive an engine, the more it costs to maintain at the base. The model provides an estimate of base maintenance cost

per engine flying hour consumed by the fleet. In a 15-year life-cycle cost estimate, consumed engine flying hours will exceed restored engine flying hours because an engine is not returned to the depot to be restored when it is about to be scrapped.

TOA and ΔTOA do not enter directly into the depot and base models, but do enter indirectly through CPUSP, thus providing some measure of state-of-the-art impact on cost. CPUSP entered both the depot and base models; thus, it would appear that attention to designing an engine to a production unit cost would reap benefits in the ownership area.

AN EXAMPLE

Using the models derived, Table 3 presents a comparison of life-cycle cost breakdowns for hypothetical fighter engine programs of the 1950s, 1960s, and 1970s. In spite of increases in development and procurement costs of engines (in constant dollars) from one decade to the next, the ownership cost portion dominates and tends to represent an increasingly larger portion of the total.* Depot maintenance cost is the reason for this trend. Miscellaneous costs were estimated to be approximately three percent of total costs for this example. Table 3 indicates that total life-cycle cost has more than doubled from the 1950s to the 1970s and that the depot is accounting for an increasing portion of that larger cost. Presently, depot costs are the largest part of engine life-cycle costs. The 1970s engine is significantly advanced in technology over the 1950s engine, and that improvement is what the military is paying for in attempting to obtain better weapon systems.

An additional calculation is shown for the 1970s engine for a case in which ATBO/MTBO has been doubled. The results show a significant ownership saving if the improvement can be realized. The models cannot show how to obtain this improvement, but indicate that it would be worth considerable additional development or CIP effort to achieve it.†

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*Overall ownership cost currently represents two-thirds of total life-cycle cost, where ownership includes CIP and whole spare engines, but not fuel and attrition, for the fighter-engine example presented. Similar results were also obtained for current transport engines.

†This example is concerned with possible variations in ownership costs. Reference 12 presents examples of how these models might be applied in looking at changes in the process of acquiring engines.

Table 3

LIFE-CYCLE COST BREAKDOWNS FOR HYPOTHETICAL FIGHTER ENGINES OF THE 1950s, 1960s, AND 1970s

	Cost for Engine with 750 ATBO, 1200 MTBO						Cost for Engine with 1500 ATBO, 2400 MTBO	
	1950s		1960s		1970s		1970s	
Cost Element	$M	%	$M	%	$M	%	$M	%
Itemized Cost Breakdown								
RDT&E	311.7	8.9	360.3	7.2	428.1	5.4	428.1	7.0
Procurement								
Install	983.3	27.9	1429.7	28.5	2273.1	28.9	2273.1	36.9
Spares	245.8	7.0	357.4	7.1	568.3	7.2	568.3	9.2
CIP	252.2	7.2	330.6	6.6	428.0	5.4	428.0	7.0
Depot	1066.4	30.3	1708.2	34.0	3052.6	38.8	1629.0	26.5
Base	558.1	15.9	690.2	13.7	897.9	11.4	646.2	10.5
Miscellaneous	102.5	2.9	146.3	2.9	229.4	2.0	179.2	2.9
Total[a]	3520.0	100.0	5022.5	100.0	7877.5	100.0	6152.0	100.0
Cost per Engine Flying Hour Consumed[b]								
Acquisition	216		298		450		450	
Ownership	371		539		863		575	
(Base and depot maint)	(271)		(400)		(658)		(379)	
Total LCC	587		837		1313		1025	

NOTE: Assumed for all programs:

1975 dollars	6 M EFH consumed by fleet
5-year development	5 M EFH restored by depot
15-year operations	1935 engines (including flight test and spares at 25%)
Advanced engines	No fuel or attrition included
90% learning (production)	

[a]May not add exactly because of rounding.

[b]Average cost for total program.

These theoretical examples, while intended to reflect real engines acquired in these decades, were constructed to show trends on a comparable engine-program basis from decade to decade. Real engine programs will not necessarily indicate similar results for a particular decade if their programs are significantly different from the assumptions shown in the table.

IV. COMMERCIAL AIRCRAFT TURBINE ENGINE LIFE-CYCLE EXPERIENCE: A COMPARISON WITH MILITARY PRACTICE

Commercial airline peacetime operations provide an environment in which benefits can be measured more quantitatively and related to life-cycle costs. The airlines offer a service, providing a degree of safety and dependability, at a price. Their success can be measured over time in their ability to stay in business, earn a profit, meet some amount of competition, and grow in a regulatory climate. To some degree, then, it is possible to measure success quantitatively much as costs are measured.

COMMERCIAL LIFE-CYCLE PROCESS

The airlines purchase engines and engine parts as someone might an automobile and its replacement parts. Having made the initial choice, there is then less latitude in purchasing replacement parts. The airlines do not pay directly for the development of engines and airframes as a specific cost as the military do, but in reality, their purchase prices cover all or some portion of that development cost. The manufacturer's price for new engines and parts covers not only the cost of design, development, and manufacture, but also the company's profit, incremental costs for component improvement, IR&D, and a margin to cover the warranty the company provides to the airline. The warranty may take the form of a guaranteed maximum material cost per flying hour to the airline for a certain period of time and/or number of flying hours. The manufacturer is liable for some portion of material cost exceeding the maximum. Engine companies, for example, may guarantee to repair or replace an engine part at no cost to the airline if it fails within an initial period, and to refund some portion of the cost for that part up to some additional flying time, after which the engine company is no longer liable. These warranties vary, depending on the coverage the airline desires and is willing to pay for, and on the engine company's desire to conclude a sale. The actual value of a warranty is therefore a matter of negotiation between the airline

and the manufacturer for each particular situation, since there is a wide area of interpretation concerning primary fault and secondary effects and who pays for what portion of the total cost involved.

It is readily apparent that the life-cycle process differs substantially for commercial and military engines. The military pay for the development, component improvement, and IR&D separately, and they are required to oversee these expenditures. There is no warranty coverage for military hardware except in the case of failure of a brand-new item. The IR&D and CIP are funded separately, but in reality are obtained by the engine companies as add-ons to the selling price of a military engine, once the basic selling price and procurement quantities for a given year have been established, and the total cost and apportionment of IR&D and CIP programs have been approved.

TIME-OF-ARRIVAL FOR COMMERCIAL ENGINES

The technology for the design of aircraft turbine engines--at best an imprecise art--has improved steadily during the past three decades in a continuing quest for higher quality. During this evolutionary development, the demand for performance has dominated military acquisition, and usually under highly constrained schedules; the manufacturer's effort to meet both performance and schedule requirements exposes engine programs to the risk of serious cost growth, while relegating to lesser importance other quality characteristics of durability, reliability, maintainability, safety, and concern for environmental effects.

Commercial engines are designed to a different balance of criteria. High performance is still desirable, but safety and cost considerations make durability, reliability, and maintainability critical characteristics. Government-mandated safety requirements are a basic consideration in commercial flight, with cost as the strong second consideration. Since the same manufacturers provide both military and commercial products, the design differences between the two are not a matter of a different technology base, but of adapting the available technology to fit the two sets of circumstances.

How different are commercial demands from military demands concerning the quality of an engine? To aid in answering this question, the TOA approach was employed.

A total of 11 commercial engines were added to the data base of 26 military engines. An equation was obtained that uses the combined data base and employs a dummy variable for the commercial engines to differentiate them from the military. The resulting indication is that commercial engines are more conservative than military engines. The dummy variable has a positive value of about ten quarters, indicating that commercial engines are about 2-1/2 years behind military engines in their TOA. The lag could be explained in either of two ways: either the commercial engine achieved the same performance level as the military but received certification 2-1/2 years later; or, for the same development milestone, the commercial engine design traded off reduced performance for greater durability, reliability, and maintainability, which affect safety and cost. It does appear that engine designers apply the technology base differently in designing a new commercial engine.

This finding has significance for the current military trend of designing to a life-cycle cost, because the trend will require engine designers to make quantitative tradeoffs among aspects of quality other than performance. Since this model is attempting to relate time to multiple design objectives, a crucial task for future work is to quantify the characteristics of durability, reliability, maintainability, safety, and environmental impact so that they can be introduced into a time-of-arrival model along with performance considerations.

COMMERCIAL OWNERSHIP

The primary concern of an airline is to make a profit, and the primary operational benefit measure for an airline is aircraft utilization. For engines, utilization is usually expressed in flying hours or operating cycles. The commercial flying-hour experience is considerably different from the military. The airlines follow established routes with known demand rates for flying-hour segments and takeoffs and landings over a given calendar period. The military has varying requirements, except perhaps for a portion of the fairly well-scheduled MAC fleet. The airlines accumulate engine operating hours faster than the military, even for comparable aircraft. The airlines fly about

three times more hours in a given year than the MAC fleet aircraft, and ten times more than supersonic fighter aircraft.

OPERATIONAL PRACTICE

Commercial operational practices and procedures also differ from the military. Operationally, the airlines require pilots to devote considerable "tender loving care" to their aircraft. The throttle is used only to the extent made necessary by gross weight, field length, altitude, and temperature for takeoffs and landings. On almost all Air Force aircraft, there is no way to determine how much hot-time the engine sees during a known mission profile, although there has been some initial work on engine diagnostic systems that count throttle excursions.* Squeezing out the last few percent of power is considered very costly to engine hot-section life. Airlines require flight crews to monitor engine performance in flight and to supply data for trending analysis of engine performance after each flight. Careful throttle-management enables the airlines to achieve important dollar savings by trading performance for temperature (and thus parts life). The Air Force could do the same. Since the military operation of an engine is even farther up on the higher end of the power curve (approaching maximum performance), even a nominal reduction in throttle excursions could yield a very significant improvement in parts life.†

MAINTENANCE PRACTICE

Commercial maintenance practice has been extolled as an example from which the military might benefit. Airline maintenance practice today has turned away from the military's hard-time philosophy (certain actions are taken at certain times regardless of how well the engine is operating) toward what is generally termed on-condition maintenance.

There is some semantic confusion concerning the meaning of on-condition maintenance. Current airline maintenance procedures actually fall into three areas of consideration: maintenance of life-limited,

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*The F100 engine on the F-15 aircraft has such a counter, but it is not yet working well in operational practice.

†Several examples are already available for TAC and SAC aircraft.

high-time parts; condition monitoring of certain non-safety-of-flight parts for which there are no fixed time limits; and on-condition maintenance of critical safety-of-flight parts that require regular periodic inspections. The various airlines cause some confusion by using these terms somewhat differently, but in general they distinguish between on-condition maintenance and condition-monitored maintenance related to the level of inspection activity and impact of the part on safety-of-flight.

The intent of the on-condition maintenance program is to leave the hardware alone as long as it is working well and symptoms of potential problems are not developing. This philosophy is *not* one of "fly-to-failure" where safety-of-flight items are involved. This maintenance program is expected to reduce the shop visit rate, determine which parts are causing removals and at what time intervals, increase the engine's accumulation of flying hours and cycles by maintaining its availability on-wing, reduce secondary damage resulting from serious failures, and maintain and improve the normal distribution of failures expected for engines.

Prolonging the interval between shop visits for maturing commercial engines is equivalent to increasing the average time between overhauls in the military. The result of this action is to prevent the truncation of the engine overhaul distribution caused by fixing the maximum allowable operating time between overhauls and the subsequent resulting large increases in the engine removal rate when maximum hard-time overhaul is reached. The commercial practice could therefore provide insights to the military in terms of what parts are determining failure rates and how CIP funds might best be apportioned among various engine problems.

On-condition maintenance has several specific requirements: 1) periodic on-aircraft inspection of engine safety-of-flight areas at ground stations (borescoping, X-ray, oil sampling and analysis, careful examination of the engine); 2) engine performance checks and data-gathering in flight, using such data for trending analysis at a central data processing center (usually at the main overhaul facility) to anticipate problems before they occur; and 3) tracking of critical parts by part number to keep account of the amount of operating time and operating cycles the parts have undergone.

When an engine problem is discovered or anticipated from trending analysis, the engine is removed from the airframe and repaired at a base if possible (by replacing a part or module, which is then returned to the shop); or the entire engine is sent back to the shop; or the aircraft is scheduled for a flight to the maintenance base so that the engine can be removed and another engine installed overnight with no loss of scheduled flight time. It is estimated that 90 percent of engine repair activity is performed at the shop; very little fixing of hardware is done at bases except removal and replacement of engines or modules or of major parts easily reached with minimum disassembly. (The base also performs other tasks primarily concerned with the ground inspections, and handles lube, oil, and maintenance associated with day-to-day activities.) It may be asked why the Air Force cannot operate in this manner. The reason is that the airlines operate in a relatively stable peacetime environment. Some Air Force units may be able to operate in a similar manner, but others must be prepared to be self-sufficient in an overseas wartime contingency and thus are required to maintain a larger labor force at the base level.

When a commercial engine is returned to the shop, the data system is expected to furnish the engineering and maintenance people with records of how much operating time has accumulated on particular parts, so that they can judge whether to fix only the part which is broken (or that they anticipate will break shortly) or to fix other parts as well while they have the engine in the shop. They attempt to rebuild the engine to some minimum expected operating time.

Newer commercial engines are of modular design. "Modular" means that the engine can be readily separated into major subassemblies. The intent is to add flexibility to maintenance procedures at the shop and at the base. Engines can be removed and replaced overnight and modules can be "swapped out" at a base in several days, with only the modules returned to the shop for repair. One result is that airlines turn engines around faster than military depots (15 to 30 days versus 45 to 90 days), and consequently require substantially fewer spare engines.

The Air Force has begun to procure modular-designed engines; the F100 engine on the F-15, and the F101 on the B-1, are examples. The

Air Force is now implementing a modular engine maintenance information system like that of the airlines for keeping track of the operating time on parts and for helping in decisions concerning the operating life appropriate for each module and engine. The Air Force will have to be able to do this kind of analysis at the depot and base if they plan to adopt the commercial maintenance philosophy regarding modular engines and, especially, regarding on-condition maintenance.

Maintenance experience and skill levels are very high for the airlines in their central shops. Most mechanics are FAA-qualified, have a long continuity in service, and with their years of experience get to know the individual engines and aircraft, since the fleet is not so large for a given airline. The civilian labor force at the Air Force depot also has considerable continuity of service, but the vast inventory and the current practice of completely disassembling an engine during overhaul and reassembling it with different parts prevents them from getting to know individual engines--besides which, the engine changes its identity every time through the depot. It is not clear how much of an edge this gives the airlines, but airline people consider it substantial. The commercial work force is also more flexible about scheduling overtime during peak periods and laying off during slumps. The military depot does not have this flexibility in the short term.

Several airline officials have expressed concern that perhaps they have gone too far too fast with on-condition maintenance as applied to current high-bypass-engine experience. Their worry is that they might be merely postponing certain problems to a later date. They believe they are obtaining more operating hours, but at a cost: when an engine finally does return to the shop, perhaps more has to be done to it in terms of parts replacement than if it had come in sooner. The problem is to determine the "optimum" point. The military attempt to do so by setting an engine MTBO at some point that the user and supplier believe is optimum in terms of operational availability on the one hand, and the amount of work required when it is returned to the depot, on the other hand. The choice lies between two extremes; a short-fixed-time philosophy is one, and on-condition maintenance running to failure or

almost to the anticipated point of failure is the other. There may be some optimum intermediate point derived from a combination of hard-time and on-condition maintenance, and this optimum could vary, depending upon the individual airline or military situation. One airline's (or service's) optimum is not necessarily another's because of differences in route structure and operating conditions (mission), utilization of the fleet, economic environment, and so forth. At any rate, it would appear desirable for the military to move away from its strict hard-time philosophy, but no doubt there is some point on the on-condition maintenance spectrum beyond which it may not be desirable to go for the sake of economic efficiency. Appropriate data are required to assist in seeking this optimum.

COMMERCIAL ENGINE COSTS

What does it cost the airlines to own and operate their commercial engines? The question is more difficult to answer than would first appear, even though manufacturers preserve a great deal of engine cost data over a substantial period of time for their cost analyses. Airlines are also required to provide certain cost data to the CAB, separated into certain cost categories.

Because accounting practices, operations, and economics vary among airlines, however, only the individual airline will know fully what its costs are under its own accounting practice, route structure, operating environment, seasonal adjustments, and economic conditions.

Therefore, difficulties arise in attempting to use airline cost data directly. The purchase price of an engine that an airline reports to CAB may reflect the cost of the entire pod, which is the total installed engine in its nacelle ready for mounting on the aircraft wing, or it may reflect the bare engine and certain spare parts. It may also include, as in the case of reported Air Force contract prices, spare parts and accessories, technical data, and field service costs. Thus, it may be difficult to use the aggregated data reported to CAB to arrive at standardized procurement costs that will be comparable among the commercial airlines. At least an estimate can be obtained, however, if it is known whether the purchase was for a bare engine or a podded

engine, and if some idea can be gained of what additional costs are involved in the purchase price.

The matter of proprietary information can be a further stumbling block. To gather information on military engines for this study, it was necessary to go to the manufacturers for disaggregated, homogeneous, longitudinal data. They were willing to supply military data on a proprietary basis, but they are not willing to supply commercial cost data at all, except in the most unusual circumstances and then only on a very limited basis.

In sum, the analyst faces the dual difficulty of determining the content of the CAB data and of obtaining information the airlines and manufacturers consider highly proprietary. Thus, *the major problem in comparing commercial and military engines is generating comparable costs*. At present, the most pressing need is to understand what the commercial cost data actually include; nor is it sufficient to do so for only a one-year or two-year cross-section. Cost analysts in both the engine industry and the airline industry agree that five to seven years worth of historical data are needed to gain a reliable picture of the trend for a particular piece of equipment. This appears to be true for both technical and economic reasons.

ANALYSIS OF AVAILABLE DATA

Figure 2 depicts a rough breakdown of typical 14-year life-cycle costs for the older first- and second-generation commercial turbojet and turbofan engines. New third-generation high-bypass engines may be different in terms of cost magnitude and proportions, and their cycle may be extended in order to cover their higher costs, with depreciation spread over more years--perhaps 16 rather than 14. The figure reveals that 75 to 80 percent of cost is ownership. It should be recalled, however, that the procurement cost of the engine includes allocations for development and IR&D, and ownership costs also include, besides CIP and warranty add-ons, a charge for development; consequently acquisition and ownership costs are not cleanly defined even for airlines. It is interesting to note from the figure that an airline buys an engine twice over in spare parts alone during its operational life.

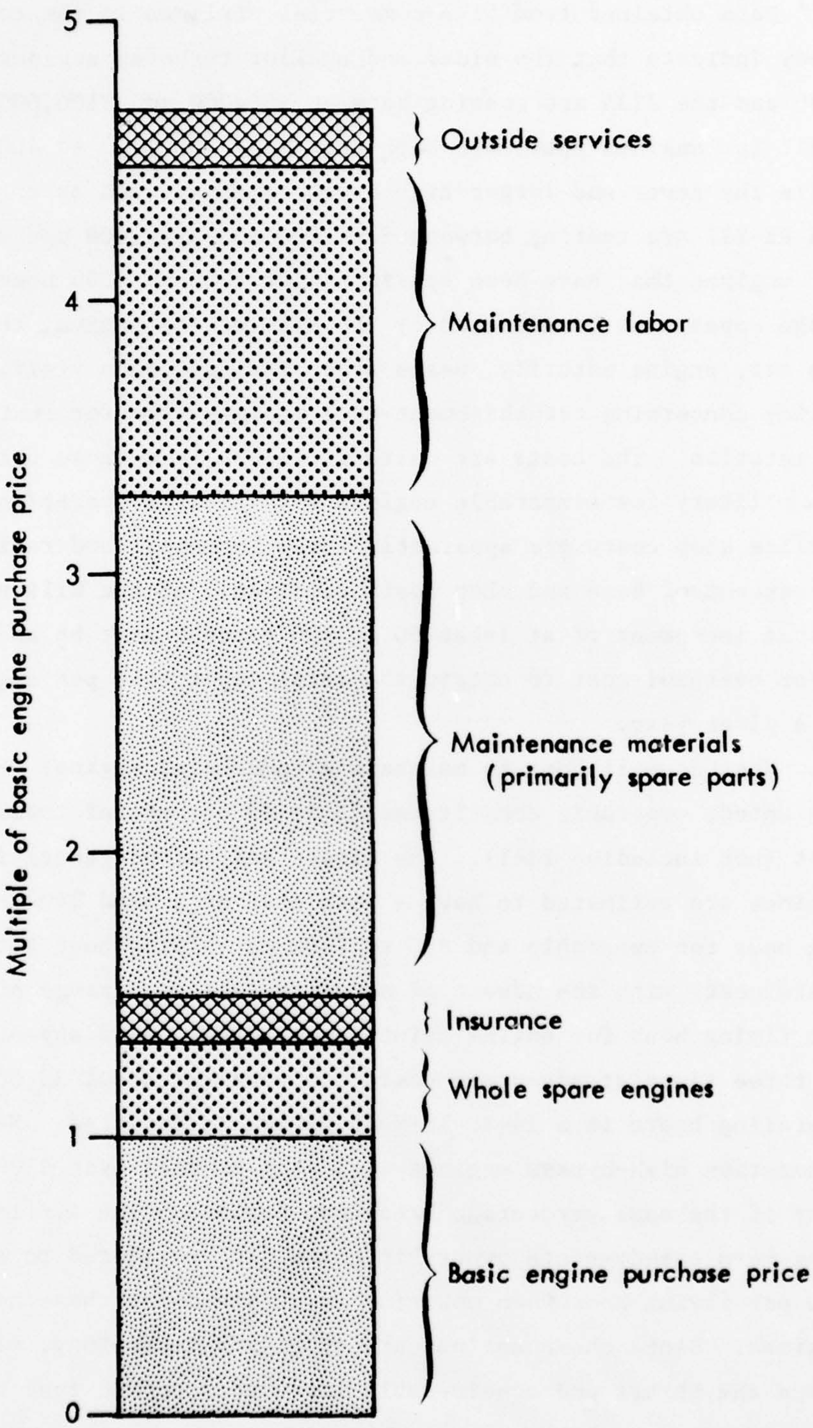

Fig. 2—Typical 14-year life-cycle costs for first- and second-generation commercial turbojet and turbofan engines (from Ref. 5)

Data obtained from five commercial airlines in the course of this study indicate that the older and smaller turbofan engines such as the JT8D and the JT3D are costing between $50,000 and $100,000 per shop visit for engines that have been operating for 2000 to 4000 hours, while the newer and larger high-bypass engines such as the CF6, JT9D, and RB-211 are costing between $100,000 and $200,000 per shop visit for engines that have been operating for 1000 to 2000 hours. The cost range appears to be affected by the size of the engine, the state of the art, engine maturity, usage since the last shop visit, and airline policy concerning refurbishment to a minimum time for next shop visit expectation. The costs are quite different from those obtained from the military for comparable engines with similar operating experience. Airline shop costs are apparently fully burdened* and reflect around 90 percent of base and shop costs combined. At the military depot, a cost increment of at least 50 to 100 percent must be added to the major overhaul cost to obtain the total depot cost per engine processed in a given year.

What does it cost to maintain a commercial engine? From the data presented, ownership constitutes 75 to 80 percent of total life cycle cost (not including fuel). The first- and second-generation commercial engines are estimated to have a peak cost of around $40 to $80 per flying hour for ownership and $50 to $100 per flying hour total. Steady-state costs with the advent of maturity fell to a range of $20 to $30 per flying hour for engine maintenance. Peak costs appear to be two to three times steady-state costs. A total of about 35,000 to 45,000 operating hours in a 14-to-16-year period is expected. New third-generation high-bypass engines will peak at well over $100 per flying hour if the same percentage breakdown applies. The airlines hope that long-term steady-state ownership costs can be reduced to around $40 to $50 per flying hour when maturity is attained for these new generation engines. Since these engines are of higher technology, with at least twice the thrust and considerably improved specific fuel consumption,

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*Including all allocated materials, back shop labor, and overhead, except for major modifications, which are treated as investment rather than operating expense for tax purposes.

they are expected to be well worth the higher cost to the airlines in the service they will provide with the new wide-bodied transports.

In short, it is possible to construct a cost profile for the life-cycle of an engine. The data examined here are consistent with the general trend indicated regarding maturation and steady-state operation. This commercial cost profile of peak, steady-state, and average costs should be helpful in attempting to understand overall military life-cycle costs, which should behave similarly (at perhaps a higher cost level). The use of only cross-sectional data to estimate costs for a given engine can be misleading if the engine's relative position in its overall life cycle is not understood, and if the data are heavily weighted to the steady-state situation.*

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*In the military models developed in this study, both the depot and base equations contain the term OPSPAN, which controls for the time effect to some extent. However, the data were heavily weighted by programs that had arrived at fairly steady-state conditions.

V. RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

This study has presented an integrated methodology that incorporates the effects of state-of-the-art changes; the purpose of the methodology is to provide visibility to the weapon-system planner in terms of magnitudes, proportions, and trends in aircraft turbine engine life-cycle costs, so that the planner has flexibility in trading off quality, schedule, and cost in the selection of new engines.

The CERs obtained include engine characteristics and schedule variables known to be important to each particular phase of the engine's life cycle. They include measures of the quality (benefit sought) and the state-of-the-art advance represented by a particular engine. Quality, in its fullest sense, encompasses not only performance but also durability, reliability, maintainability, safety, and concern for environmental effects. The overall quality/schedule/cost balance of a particular engine thus reflects the early planner's estimate of the value of the product ultimately delivered to the user. The study deals primarily with the military engine, for which quality has been highly synonymous with performance, but it also addresses the commercial engine, for which the other attributes of quality predominate.

For a new engine program that will have an operational lifespan of 15 years, the findings indicate that:

- The magnitude and proportion of costs associated with an engine are significantly larger than and different from those found in previously published studies. For instance, engine depot and base maintenance costs, not including fuel and attrition, will exceed engine acquisition costs.*
- Depot costs alone will exceed procurement costs.
- As much money can be spent on engine component improvement

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*All costs are expressed in constant dollars. Discounting may change some findings, depending on the distribution of cost outlays over the time horizon of interest and the discount rate assumed.

during its operational use as was spent to develop the engine to its initial model qualification.

- If component improvement and whole spare engine procurement are considered ownership costs, then ownership currently constitutes at least two-thirds of total engine life-cycle cost.
- Application of the models obtained in the study indicates that that there is a continuing trend in the direction of higher ownership cost, measured both in absolute dollars and as a percentage of total life-cycle costs. Increasing depot cost is the reason for this trend. To break it, the Air Force will have to depart significantly from its current ownership practices at both depots and bases.

For a variety of reasons, there is a wide range of acquisition and ownership costs associated with the various engines currently in the USAF inventory. These costs can vary by over an order of magnitude across engine programs and applications. These costs are affected by the engine quality desired, the mission, the schedule imposed on acquiring a new engine, and the operating and support policies selected. During the early years of the life cycle, the ownership cost in terms of dollars per flying hour (the most widely used yardstick) may far exceed the steady-state average costs achieved when an engine has matured. These aspects of life-cycle analysis must be more fully understood if improved analytical results are to be obtained and applied to new engine selection.

Intuitively and statistically satisfying results were obtained from modeling performance/schedule/cost relationships for the development and production of military engines. Somewhat disaggregated, homogeneous, longitudinal data were available from contractors. Application of the development and procurement cost models obtained to new engine programs indicates that an advanced engine is significantly more expensive to develop and procure than a state-of-the-art engine.

Mixed but promising results were obtained in modeling ownership costs for military engines. The available data were aggregated, heterogeneous, and cross-sectional (only one year of data was available

in some instances). Component improvement program costs prior to 1969 contained expenditures for performance enhancement and additional applications, as well as those costs related to corrections of deficiencies, reliability improvement, and cost reduction. No attempt was made in the present study to separate these costs. Depot maintenance costs were more detailed and amenable to analysis than base maintenance costs (which were fairly gross estimates). For new engines, the data indicate that depot costs can be expected to exceed procurement costs, and base costs, while usually less than depot costs, are still significantly large. Because the depot and base models were obtained with sparse data, they must be used cautiously until better data are obtained with which to develop improved models.

The results of the analyses indicated that: 1) careful definitions of quality (benefits) and costs are needed at the outset; 2) there is a pressing need for better ownership, cost, and benefit data for military engines extending over a longer time period, i.e., disaggregated, homogeneous, longitudinal data; 3) it is considerably more expensive to own current engines in the military than previous studies have indicated; 4) the maturation process must be more fully understood; it takes a long time for engines to mature (commercial practice indicates 5 to 7 years), and thus average costs over an operational time span are significantly higher than mature-engine steady-state costs; 5) it is recognized that significantly different peacetime/wartime considerations must be applied when attempting to compare the benefits obtained from military and commercial experience; nevertheless, the military can benefit from certain commercial practices in areas such as life-cycle management, engine power management for flight operations, and on-condition maintenance; and 6) there is a need for improved price escalation factors that provide the appropriate proportions of labor and materials content and also relate to the particular phase of the life cycle.

A review of operating and maintenance techniques and policies for all using commands is desirable to assist in bringing on-condition maintenance and power management to fruition. Progress is already being made in this area. Engine diagnostic systems could assist in obtaining

significant improvements in these areas if they live up to expectations. To realize full life-cycle cost savings, consideration must be given to appropriate manning levels in determining the impact of any new policies.

It is recommended that USAF pursue, in its organizations at all levels, an improved understanding of *life-cycle analysis* and that it move quickly toward obtaining better data with which to do such analysis. This must involve attention to appropriate benefit measures as well as inclusion of all relevant cost elements.

This study by no means represents the final word on this very large and complex subject. It is recommended that the current life-cycle analysis effort be continued. A richer model of engine quality embodying commercial as well as military design characteristics would be a worthwhile objective. An improved understanding of engine life-cycle cost *visibility* has been achieved (magnitude, proportions, and trends) and important cost-drivers have been identified, but much still needs to be done in understanding leverages between phases so that *control* of costs can be achieved. As yet, no one is able to specify exactly how much can be gained by spending more time and money earlier in development in order to improve operational capability and reduce ownership cost. The data currently available are not sufficient for designing engines in the light of total life-cycle benefits and costs, and there will be a significant time lag in obtaining improved data. Meanwhile, until better data are obtained for costing new weapon systems currently being contemplated for the 1980s, a philosophy of designing an engine to a production unit selling price for the engine quality desired is a reasonable alternative, provided that "artificial" design compromises are not allowed that might reduce production cost but would obviously hinder attempts to reduce ownership cost.

The methodology obtained in this study is only a beginning toward understanding and alleviating the problem of the large and increasing costs of new weapon systems. For the present, the methodology can provide cost estimates for future military engines to be acquired and owned in a manner like that of the past; it can also provide some measure of the change in costs if acquisition or ownership or both were

conducted differently enough to encompass other parameters of interest (e.g., performance/schedule tradeoffs). Such results can be extremely useful to a weapon system planner during early consideration of new systems. The approach and findings of this study may also be useful for the insights they may offer into the acquisition and ownership of other system components during consideration of new weapon systems.

Future work should focus on improving the benefit and cost data and the CERs, in order to give the planner more quantitative information regarding tradeoffs that involve interactions between the acquisition and ownership phases of the life-cycle process. So equipped, the planner can make better-informed decisions regarding acquisition and ownership policies.

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